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Flame and incendiary weapons have been used since the dawn of civilization. Cavemen used flame and burning coals to drive off animals and man alike. Firebrands fastened to the tails of foxes were used to burn the crops of the Philistines about 3,000 years ago. Armies attacking and defending fortified cities threw upon each other burning oil and flaming fireballs.

The most effective flame agent for warfare was "Greek Fire" invent[illegible] about 600 B.C. It is believed to have contained readily inflammable substances such as pitch, resin, petroleum, as well as sulfur and quicklime. The quicklime on contact with water generated sufficient heat to ignite the mix. It was difficult to extinguish the "Greek Fire" because water increased the reaction of quicklime and spread the petroleum. "Greek Fire" was used extensively in the wars of the Middle Ages and was employed until the introduction of gunpowder in the 13th century.

Flame and incendiary weapons were only sparingly used from the 15th century until World War I. Although historical records are replete with accounts of flame and incendiary attacks against materiel and personnel targets, the defeat criteria and energy requirements for the thermal defeat of military targets are practically nonexistent.

In recent research efforts, an attempt has been made to reverse the age-old process of defeating combustible targets. Instead of developing an expedient system and then measuring its effects, a predictive mathematical model has been devised for a variety of targets to be defeated with flame and incendiary agents and then used to

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tailor-make the agent for the specific weapon system available or under consideration. This report presents preliminary efforts in this direction.

The research performed in the past several years has included the collection, compilation, generation, and collation of energy requirements data for thermal defeat, combustion of flammables, or weakening of physical properties of nonflammable military targets. A few of the materials considered, as well as skin burns of personnel, are cited in table 1 (references 1 through 9). These data, when used with predictive mathematical models and computer-aided studies (10), have permitted the generation of destructive indexes for a variety of target materials and the development of agent formulations for effective flame systems.

The predictive models and computer simulations (10) have guided research with thickened triethylaluminum, TEA, a pyrophoric flame agent which has led to an effective flame kill mechanism - the controlled fireball. The ability to control several key parameters such as the viscoelastic properties, a material's resistance to movement or to breakup, and the ignition delay, the time frame within which TEA first is exposed to the atmosphere and when it ignites, permits design and control of the generated fireball. The critical factor, however, is the coupling of these parameters with the total energy of the flame system to form a cloud of uniformly fine particles and to delay the ignition of these particles until the cloud has grown to the desired size, at which point all the particles react simultaneously. The net result is a very effective fireball which releases almost all of its energy within a very narrow time frame, on the order of milliseconds. In many cases, the fireball radiation pulse exists for several seconds. However, for all practical purposes, 1 second is sufficient for desired target defeat because a high heat flux absorbed in a short time allows only a small portion of the energy to be dissipated by the target.

Examples of heat fluxes generated by existing flame agents are listed in table 2 (references 11 through 15). The 1 calorie per centimeter squared-second flux level is usually present as short-range radiation and conduction through the flame gases around the surfaces of burning flame agent pools and particles. The 2 calories per centimeter squared-second flux level is about the maximum level attainable when standard flame systems dispersing large particles and pools of agent are employed against targets and represents inefficient residual burning on the target.

The calculated destructive index (10), the time integral of

the heat flux absorbed raised to some power, for various target materials has enabled effective evaluation of heat fluxes generated by flame agents. Thermal defeat occurs when the destructive index exceeds some specific value, this value and the integrand exponent both being functions of the target material under consideration.

Heat fluxes of 3 to 6 calories per centimeter squared-second have been measured during tests of the controlled fireball (14). These flux levels defeat targets more quickly and more efficiently than flux levels of 1 to 2 calories per centimeter squared-second. Defeat of seasoned oak at the 1 calorie per centimeter squared-second flux level occurs in 60 seconds representing an energy requirement of 60 calories for each square centimeter of target surface. At the 4 calories per centimeter squared-second flux level, the oak is defeated in 1 second representing an energy requirement of 4 calories for each square centimeter. This represents a 15 to 1 ratio of energy requirements and is an order of magnitude improvement in kill effectiveness.

The heat flux level generated by fireballs is dependent on the chemical composition of the fireball, the particle size of the dispersed and reacting flame agent, and the flame agent reaction rate. Fireball size also controls the flux level to a degree since, when all other factors are kept constant, the larger the fireball created, the higher the peak temperature and the peak heat flux (14), primarily radiation.

Weapons designers have avoided use of fireballs since it has been accepted that the high temperatures and high heat fluxes generated were too short in duration to be effective kill mechanisms. Standard design practice for flame weapons, to date, has been the creation of systems that produce large particles and pools of flaming agent on target surfaces. Target defeat is dependent on deposition of large numbers of particles over small target areas, literally drenching targets to produce damage and defeat by flame reinforcement. These tactics have not been effective since heat fluxes generated have rarely approached the 2 calories per centimeter squared-second flux level. At this level, much of the energy is dissipated by the target before thermal damage levels are attained. In many cases, target defeat has been negated by firefighting personnel extinguishing the individual flame sources. This last problem has been so severe that some incendiary systems have had explosive charges incorporated into their design to keep firefighters away from these burning areas.

The first use of the controlled fireball was with the M74/M202

flame system (16), which was developed for the 66-mm light assault weapon. This application was for the defeat of field enclosures and bunkers (17) and was appealing because the fireball would be contained within the enclosure for some finite period of time. Additional studies were performed with the 105-mm and the 152-mm flame round prototypes. There have been a sufficient number of experiments to confirm that controlled fireballs can be generated with all three systems.

Figure 1 presents the classical heat flux-temperature curve for a black body and includes experimental points measured in field tests (references 14, 18, and 19). Within experimental error limits, the points fall on the basic curve.

The controlled fireballs generated with the three flame systems are presented in figure 2. Also shown are the peak heat fluxes and temperatures produced by each system. A gradual increase in temperature and heat flux has been observed as fireball size increases. Furthermore, the heat fluxes attained fall within the range for effective target damage.

Figure 3 shows the flame systems together with their flame agent payloads. The two large caliber flame rounds have been fired through 2-inch-thick plywood sheets to achieve impact functioning of the round. In many of these firings, the under-1-second exposure of the plywood sheet to the fireball engulfed the sheet in flames. Fire-fighting equipment had to be used to extinguish the sustained fires.

Field tests against diesel oil in 55-gallon drums with ambient temperature and the diesel oil both at 40°F resulted in sustained fires and loss of three-quarters of the fuel. Recent Air Force field tests with a system containing about 500 grams of the Army TEA flame agent resulted in defeat of their target arrays including stacked ammunition boxes, diesel oil, and stacks of tires (20). The last tests are a portion of Inter-Service work with the US Air Force.

Field instrumentation sensors consist of precision very fine wire 0.005-inch-diameter chromel-alumel thermocouples (21), rated to 2,400°F, and millisecond response asymptotic calorimeters (22), rated to 8.1 calories per centimeter squared-second. All cited measurements have been made at ground level for outdoor trials and along the walls, the floors, and the ceilings of several field bunkers. A system to measure conditions inside these fireballs where higher temperatures are expected is being developed.

Figure 4 represents the results of one field test. The 152-mm

flame round functioned as a dynamic airburst 4 feet above ground and about 60 feet in front of the field bunker. The resulting fireball moved along the flightpath to the bunker, entered through its embrasure, flushed it out, raised its internal temperature to about 1,400°F, with a heat flux approaching 3 calories per centimeter squared-second, and exited through the opening in the rear.

A simple calculation with data from 152-mm flame round field tests wherein fireballs have been generated with 25-meter diameters and have swept downrange for distances in excess of 50 meters indicates that areas in excess of 1,250 square meters can be swept with this flame system. This area is equivalent to and often greater than the area effectively swept by Air Force 100-gallon firebombs.

Another feature of the fireball is its circumferentially uniform coverage of the target area. The thermal radiation of the fireball spreads radially so that the heat flux is approximately equivalent at equal radial distances from the fireball center. This fireball does not have gaps in its burst envelope as do systems producing large fragments or large flame particles. Therefore, there are no safe areas in the portions of the target that are engulfed and swept by it.

Most of the research has been enhanced by the use of predictive mathematical models and computer simulation studies. With them, it has been possible to develop controlled fireballs by tailoring the thickened TEA to the energy available in the weapons systems, both direct and indirect fired, on the battlefield. It is emphasized that operational demonstration of this capability with the 66-mm flame rocket and with the 105-mm and the 152-mm flame rounds has been performed.

Finally, the potential now exists for an effective all-weather standoff flame system capability for our ground forces.

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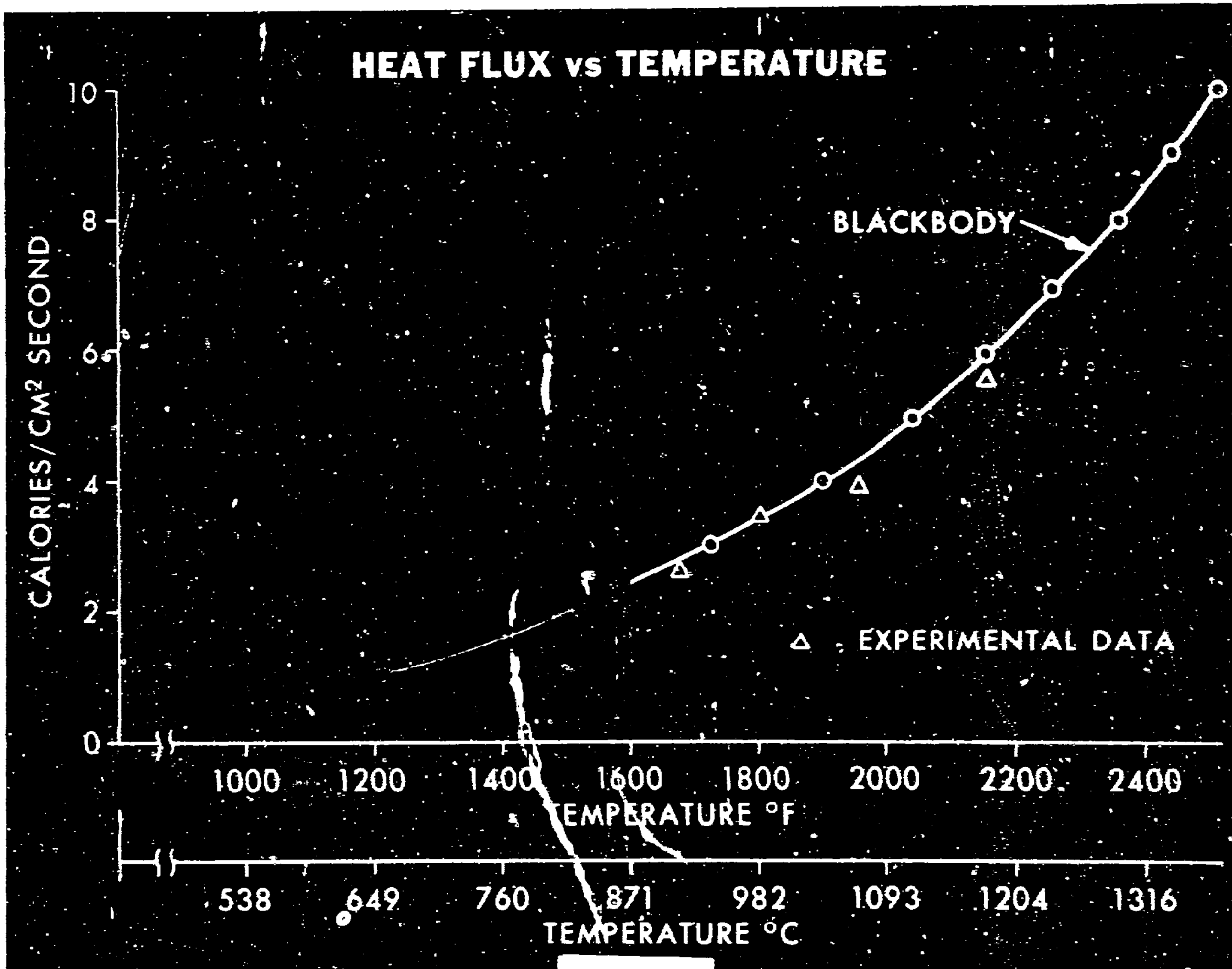
	CALORIES/CM^2 SECOND		
	4.0	2.0	1.0
RUBBER	2	10	70
OAK	1	8	60
BURNS			
3°	1.4	4	11
2°	0.7	2	5
1°	0.4	1	2

AVAILABLE HEAT FLUXES

	CALORIES/CM^2 SECOND
SURFACES OF BURNING PARTICLES	1
INSIDE BURNING PARTICLES FLAME	2
FIREBALLS	3.5 TO 5.6


HEAT FLUX vs TEMPERATURE
CALORIES/CM² SECOND
10
8
6
4
2
0
BLACKBODY
△ ; EXPERIMENTAL DATA
1000
1200
1400
1600
1800
2000
2200
2400
TEMPERATURE °F
538
649
760
871
982
1093
1204
1316
TEMPERATURE °C

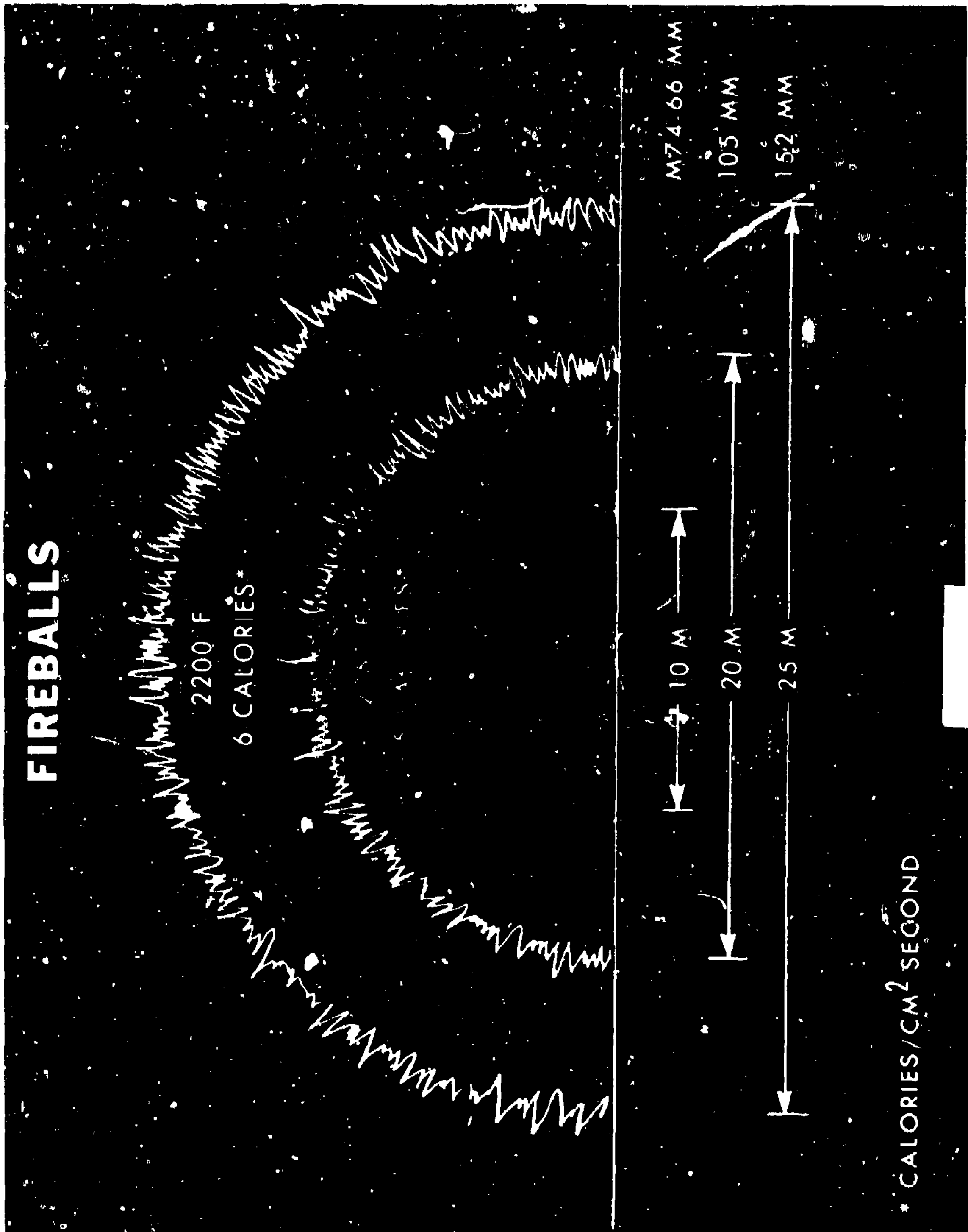
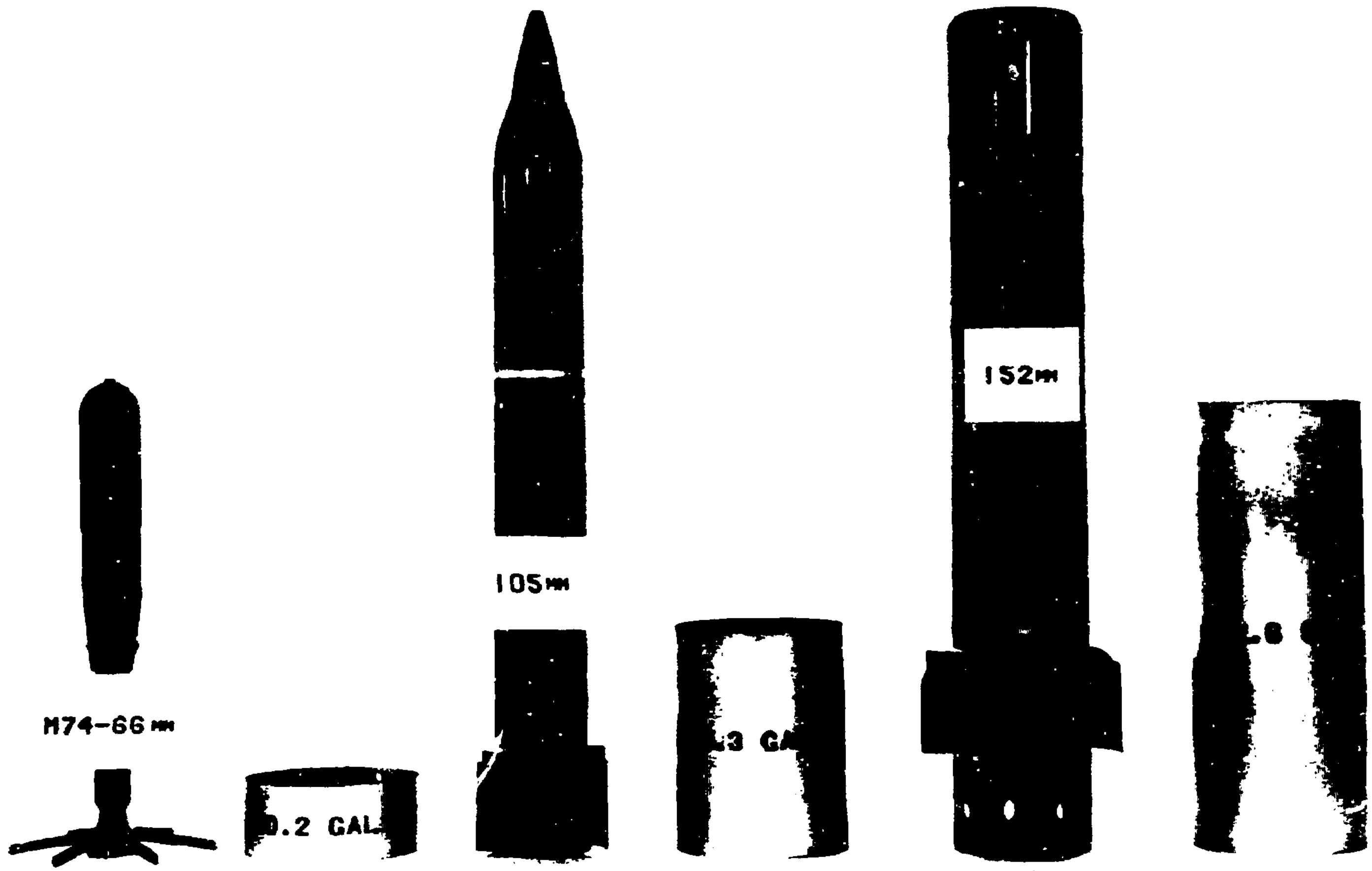

FIREBALLS
2200 F
6 CALORIES*
M74 66 MM
105 MM
152 MM
10 M
20 M
25 M
* CALORIES/CM² SECOND

FIGURE 2



M74-66 MM
.2 GAL
105 MM
152 MM

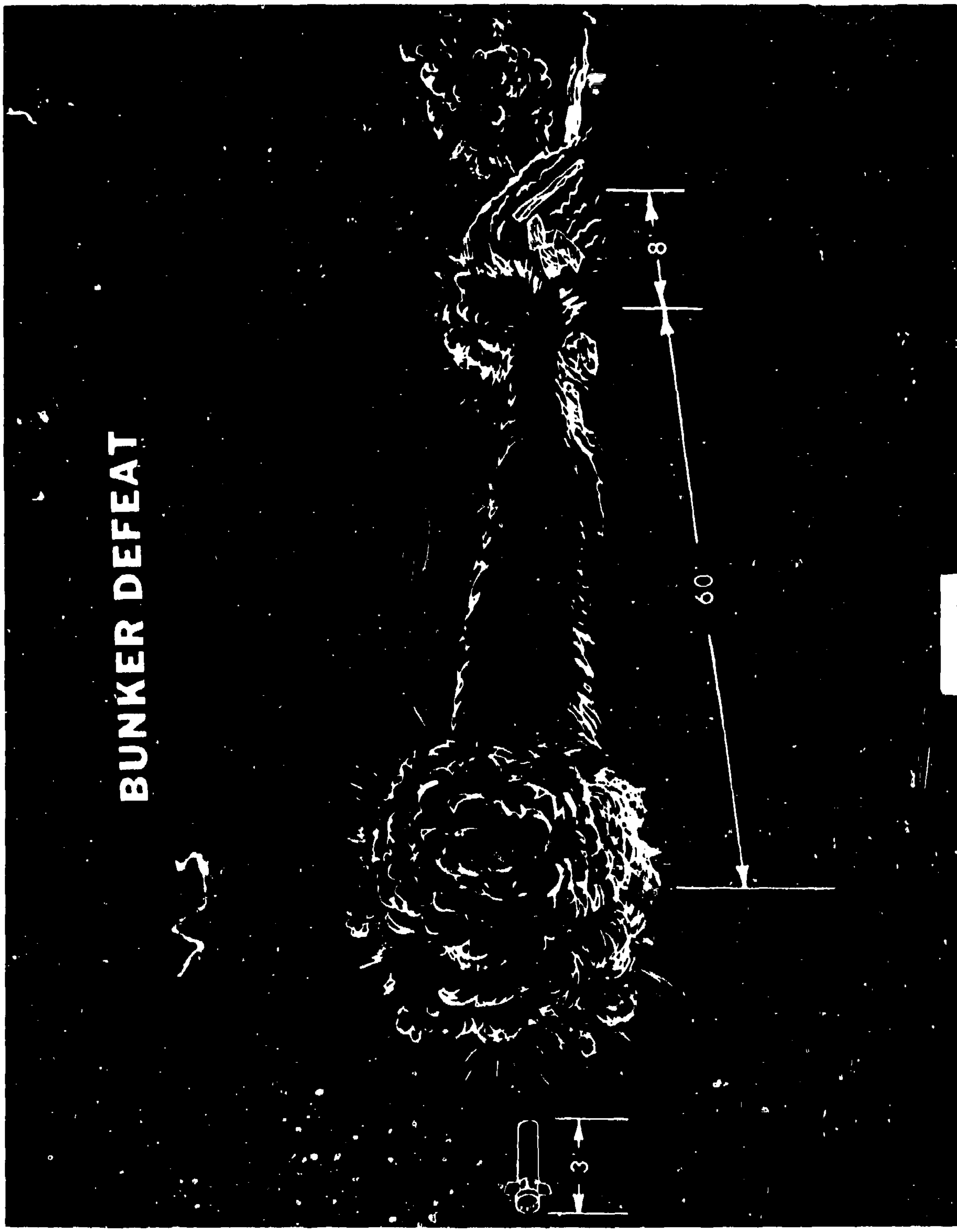


FIGURE 4